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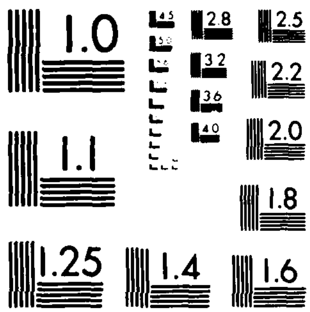

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Abstract

A new wrist design for an industrial manipulator is described that exhibits a range of compliant control. This is necessary for large industrial robots that experience a range of tool-lengths and pay-loads. The device has five and a half degrees of freedom and is structurally similar to a previous design by McCallion. Reinforced elastomeric spheres are used in the compliant platform of the unit. These display a monotonically increasing spring stiffness and can be adjusted using a pressurized fluid. Deflections in the wrist are measured using LVDT transducers. A dedicated microcomputer monitors the deflections and modifies robot sequences to correct for long-term errors in repetitive tasks.

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1 Introduction

The broad objective of this research is to improve the positional accuracy of industrial manipulators. The particular application task being addressed is the location of components in the machining and gauging stations of a small-batch Flexible Machining Cell. In fact, such tasks resemble the traditional parts-mating and assembly operations considered in detail by other investigators [1-4].

The design and construction of mechanical manipulators involves a compromise between speed, pay-load and accuracy. For example, in the particular manipulator purchased for these studies, the operational maximum speed of 127 mm/sec (50 in/min) and pay-load of 45 Kg (100 lb) can result in a placement error as high as ±1.25 mm (0.05 in). The latter figure is not atypical for commonly selected industrial manipulators; this undesirable inaccuracy arises primarily from backlash in the joints, and to a lesser degree, stiction or inaccuracies in the servo-valves.

To overcome this inherent inaccuracy a number of strategies have been employed. In the early work of Nevins *et al* [2,3] and of others [4] no changes were made to the robot controller; rather the concept of a passive, position adaptive wrist was introduced. The remote-center-compliance (RCC) device allows a shaft to be inserted into a bore by aligning the center of compliance with the shaft tip. Undesirable contact between the shaft and bore creates moments and forces but the latter self-minimize in the wrist as the unit changes its orientation. The device thus not only allows for inherent errors in the manipulator but can also cope with minor, unexpected positional variations in the components arriving for assembly. The RCC design is elegant and inexpensive and can be criticized only because, for ideal operation, component dimensions should be known *a priori*. While the device has only five degrees of freedom, the lack of axial compliance is of no major concern in shaft-in-bore assembly tasks.

As a second strategy, force measurements may be used to control the robot itself so that a workpiece held by the robot will com[illegible] the desired fashion when subjected to external forces. The effect will be just as if a compliant RCC device were being used. In fact, active control may be used in conjunction with an RCC device to improve its versatility. [2] The obvious advantage to active compliance control is that it is very flexible and may be tailored to suit the requirements of a particular task or workpiece. A number of researchers have developed active robot control schemes which typically require computing a recursive Langrangian or Newton-Euler formulation of the manipulator dynamics.[5-13] The real-time computational burden imposed by these dynamic equations is alleviated by making a number of simplifications. For example, centrifugal and coriolis acceleration terms are usually neglected. Salisbury [6] discusses a number of ways in which task-oriented compliance commands can be satisfied through active robot control. Early active control schemes used classical control techniques to servo each joint of the robot. Subsequent schemes have employed more sophisticated control techniques to improve the robot response or to allow a more simplified model of the plant dynamics.[7,12,14] All of these active compliance methods require a responsive robot with an easily modified control system. This requirement effectively precludes them from being applied to large industrial robots.

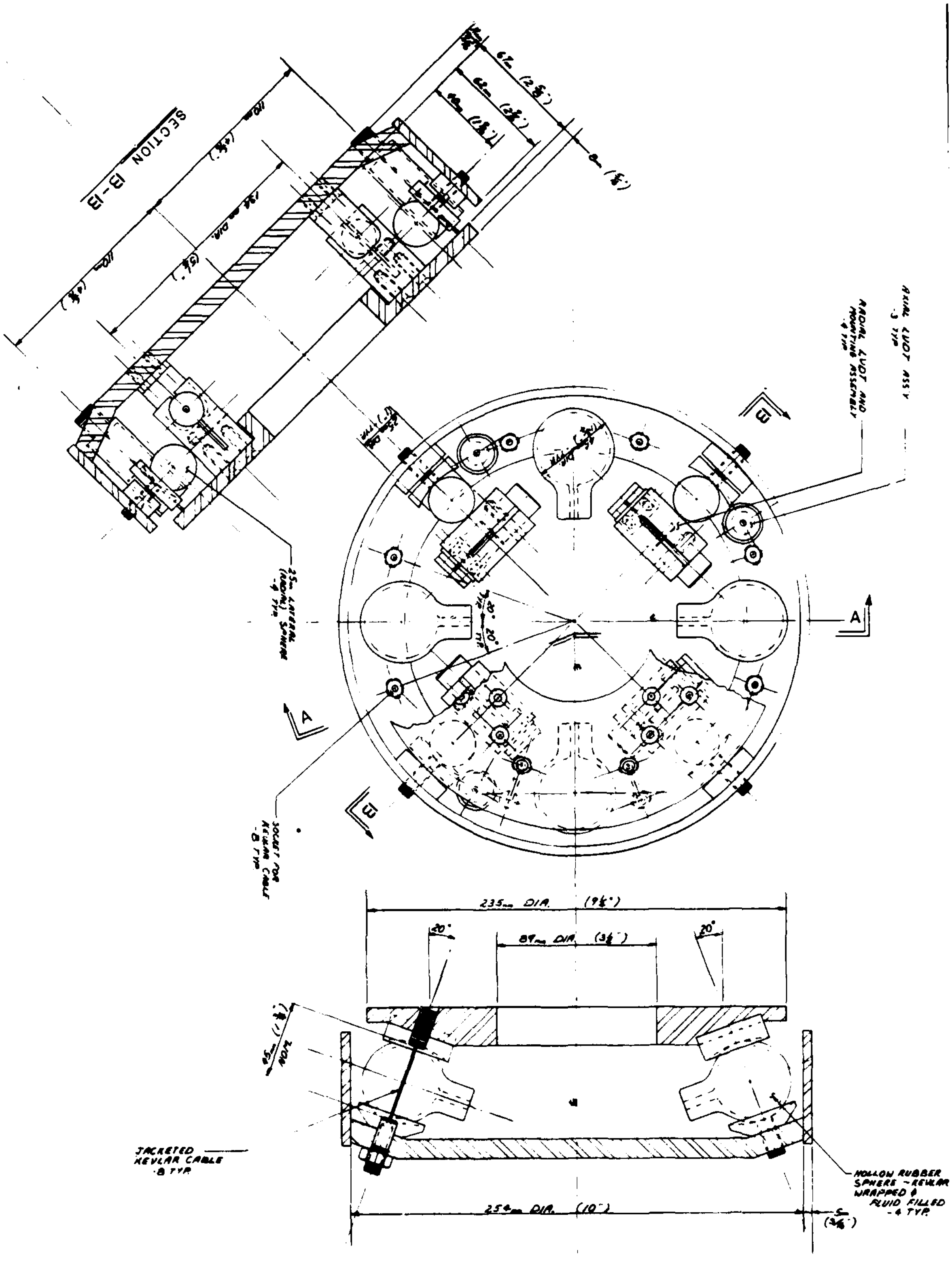

Figure 1: Design drawing of new compliant wrist

Recognizing the general unsuitability of today's industrial robots for active dynamic control Van Brussel and Simons [15] have designed and constructed a five degree of freedom wrist (no axial rotation) that contains both sensing and *direct* position control. Each wrist axis is driven by a DC-motor via a soft servo loop. Servo gain and torque saturation levels are programmable and thus the axes have an automatically adjustable "equivalent spring" stiffness. This emphasis on *wrist* control eliminates the need for complex *arm* control algorithms and it avoids ambiguous position situations arising from arm joint manipulation. The ability to adjust the stiffness for a given task is a further advantage. Evidently the cost and size of this wrist unit are large and this may hamper its application in industry.

Also recognizing the unsuitability of industrial robots for sensor based dynamic control, Whitney and Junkel [16] have proposed a stochastic control scheme in which a robot engaged in repetitious tasks could use sensory information to detect long term errors. Thus, while the rated accuracy of the robot is not improved, errors arising from long term difficulties such as robot drift or inaccurate off-line programming may be detected and subsequently reduced. This scheme is well matched to the abilities of large industrial robots and will be discussed in more detail under "System Control".

In an effort to provide a manipulator that is inherently far more accurate and much better suited to dynamic control than robots available today, Asada and Kanade [17] have recently constructed a Direct Drive Arm. Each axis is driven by a rare-earth DC torque motor and thereby avoids the usual power transmission problems of industrial robots in which back-lash and friction prevent fine control of the arm. This manipulator should be sufficiently accurate to accomplish many assembly tasks without recourse to either active or passive compliance. Nonetheless, the job of programming the robot for assembly tasks becomes easier if compliance techniques are employed. Furthermore, assembly tasks can always be found for which even an accuracy of within 0.02 mm (0.001 inch) is inadequate.

2 An Automatically Adjustable IRCC Device

2.1 Compliance Range

In this paper a design is introduced that is an extension of the Instrumented RCC concept. The new feature is that a *range* of compliant control is available in one unit. The design presented here adds mechanical complexity, but it aids assembly by reducing the need for complex software. The range of compliance available in this unit is particularly useful for large manipulators where a wide range of pay-loads imposed.

The 'compliance-range' is achieved by introducing stiff elastomeric spheres between the critical wrist components.(Figure 1) The spheres are hollow and may be automatically adjusted with a pressurized fluid. A force-deflection curve is created which is intentionally non-linear, thereby offering a range of operating stiffnesses. In a sense, the philosophy of the design is to mimic the muscle-control of the human forearm when engaged in tasks that require a range of accuracy and strength. An additional advantage that results from being able to adjust the stiffness of the wrist is that resonant conditions can be actively avoided. This feature, combined with the viscous damping of the fluid filled spheres, should help to reduce vibration problems.

In order to arrive at a fully operational, automatically adjustable IRCC device, the sub-components of the final design have been developed individually. These may be divided into the following four areas with the associated experimental work:

- Development of the LVDT system for position measurement.
- Varying the position of the compliant center.
- Development of the compliant sphere assembly.
- Overall system control and manipulator re-configuration.

2.2 The LVDT System

The primary function of the adjustable, instrumented device is to produce position information for subsequent control. Deflections are measured directly and accurately by LVDT transducers. After calibration, these deflections can be correlated with forces but the main goal is position measurement. Thus, in order to develop the LVDT system a simple version of an instrumented wrist was first constructed. Figure 2 shows this first version of the compliant wrist. The device does not project a remote compliant center and has no provision for automatic adjustment. The individual springs in the unit may, however, be manually adjusted to suit the combined weight of the gripper and part. The outer ring of the unit provides a protective housing for the inner LVDT array and it constrains the inner ring from moving more than 4.75 mm in any direction. The mechanical assembly required some "running-in" in order to seat the springs and the LVDT probes on mating surfaces, but once this was done a reliable calibration was obtained. In this simplified device radial and axial deflections were measured independently, thus facilitating the calculation of the difference between deflected and undeflected positions. Figure 3 shows a plan view of the maximum deflected position of the two rings. A brief review of the analysis of radial displacements is now given. For example, the dimension $\Delta x = x_1 - x_0$, the real displacement of the center ring is of interest. With R the inner radius (106.4 mm) of the large ring and r the outer radius of the small ring

$$R + \Delta x = r + x_1 + \varepsilon$$

where ε is a small error arising from the curvature. In Figure 3, $\varepsilon = R(1 - \cos \psi)$. Since the maximum value of Δy is 4.75 mm the maximum error is only 0.106 mm (0.0042 in), but more importantly, as the wrist seeks an equilibrium position, the error imposed by the curvature approaches zero.

Radial deflections, Δx and Δy of the LVDT axes can be transformed to robot axes using a simple homogeneous transform. Axial and bending deflections are measured with three LVDT's that define the plane of the inner ring of the wrist. The differences between the LVDT readings establish vectors whose cross-product is normal to the plane of the inner ring.

The final design (Figure 1) shows seven LVDT probes. Four are arranged to directly measure radial deflections and to detect rotation about the central axis of wrist. The remaining three are mounted axially to determine the orientation of the plane of the compliant platform following the procedure used for the first version of the wrist.

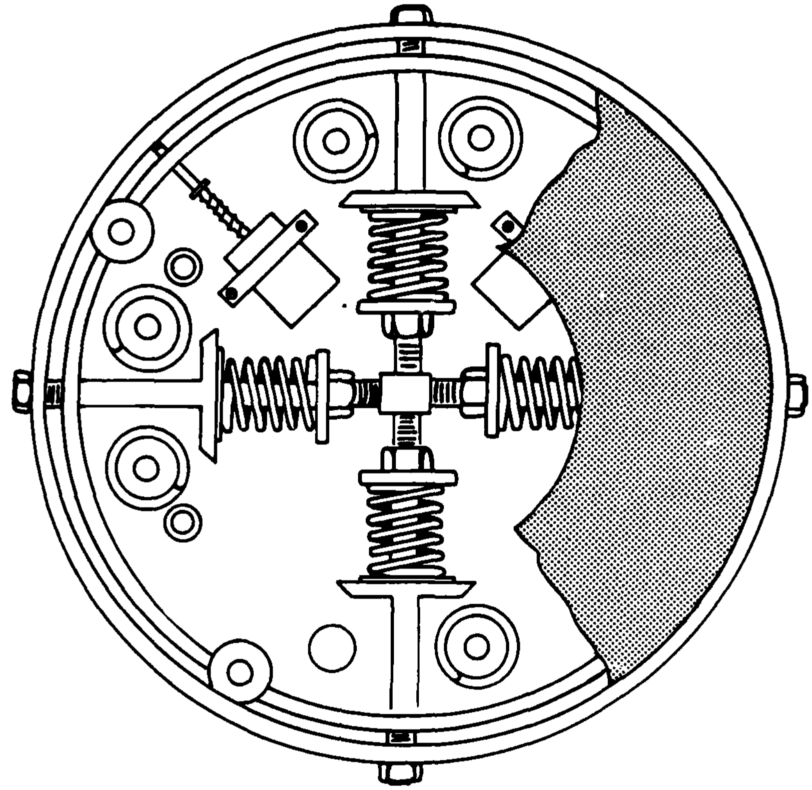

Figure 2: Plan view of simplified wrist

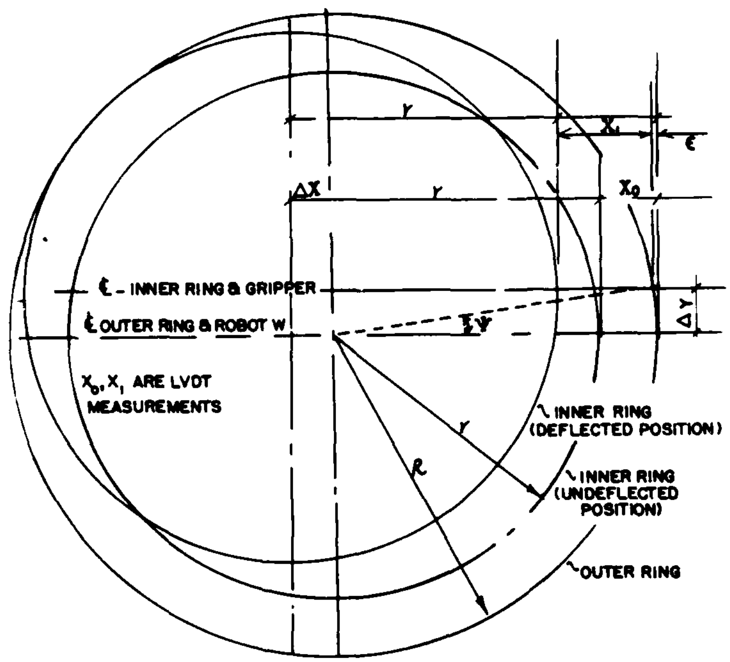

Figure 3: Deflected position of simplified wrist

Once the deflections (in terms of robot Hand Coordinates) of the gripper centroid have been calculated in this manner, the question arises: What is the optimum way of using this information to modify the robot motion? The nature of the control algorithm residing in the microcomputer is discussed in the section on system control.

2.3 Varying the Position of the Compliant Center

McCallion has discussed a compliant assembly [4] that, much like other RCC devices [2] shows nearly ideal compliant characteristics for the peg-in-hole mating task. As McCallion has shown, for the ideal compliant device the matrix correlating forces and deflections will be as follows:

$$\begin{matrix} c_x & 0 & 0 & 0 & 0 & 0 \\ 0 & c_y & 0 & 0 & 0 & 0 \\ 0 & 0 & c_z & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{\theta x} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{\theta y} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{\theta z} \end{matrix} \quad \begin{matrix} F_x \\ F_y \\ F_z \\ M_{\theta x} \\ M_{\theta y} \\ M_{\theta z} \end{matrix} \quad = \quad \begin{matrix} \Delta_x \\ \Delta_y \\ \Delta_z \\ \Delta_{\theta x} \\ \Delta_{\theta x} \\ \Delta_{\theta z} \end{matrix} \qquad (1)$$

where $c = (1/k)$ = compliance, Δ = deflection, F = force, and M = moment. McCallion's device [4] exhibits this property, but only at the origin of a *coordinate system emanating from* the surface of the compliant platform. Thus if a fairly long peg is to be inserted into a hole, undesirable deflections may occur possibly leading to jamming (Figure 4). The RCC devices of Nevins *et al.* [2] exhibit the above diagonal deflection/force matrix for a coordinate system centered at a point projected some distance remote from the actual device. Unfortunately for such RCC units, $k_{\theta x}$ and $k_{\theta y}$ are quite large, and k_z is so large that there is virtually no compliance in the z direction.

In fact McCallion's compliant device can be modified to project a compliant center and this development is one new feature of the present work. If the supporting rods are inclined inwards at an angle θ (shown by the broken lines) for a side load at the tip of the peg, the static equations become:

$$M_\theta = k_\theta \, \delta\theta = f_x[l_1 + l_2]/2$$

$$f_b = f_x[l_2(\cos\theta)/a + (\sin\theta)/2]$$

$$f_p = f_x[(\cos\theta)/2 - l_2(\sin\theta)/a]$$

where M_θ is the moment on each torsional spring, f_b is the force on each axial spring, k_z, and f_p is the shear force on each rod.

For this simplified two-dimensional structure the desired compliant characteristics are achieved if a side

force f_x causes a deflection, δx, and no other deflections. Referring to the broken lines on Figure 4, the force-deflection equations for the inclined spring system are:

$$\delta\theta = M_\theta / k_\theta, \quad \delta b = f_b / k_b$$

With f_x applied, the links are stretched or compressed. At the same time, the structure deflects through an angle, $\delta\theta$. The desired effect is that no net rotation should occur or:

$$\delta b \cos\theta - b\delta\theta \sin\theta = 0$$

Substituting for δb and $\delta\theta$ we can express the projected length of compliance, l_2, as a function of k_b,k_θ, and θ:

$$l_2 = \frac{a \sin\theta [k_\theta \cos\theta - l_1 b k_b]}{a b k_b \sin\theta - 2k_\theta \cos^2\theta}$$

This expression shows immediately that for $\theta = 0$, $l_2 = 0$. Thus in order to vary the position of the center of compliance, k_z, k_θ or θ must be changed as proposed below.

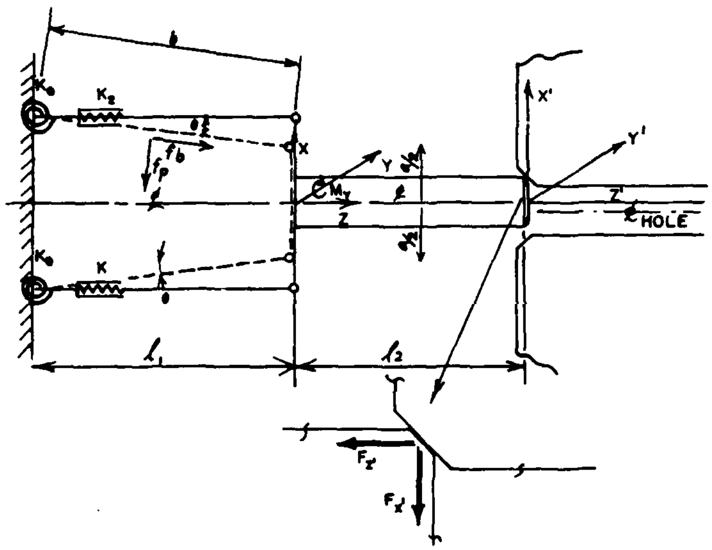

Figure 4: . McCallion et al [4] compliant device

2.4 Development of the Compliant Sphere Assembly

In the preceding section it was shown that the distance l_2 of the compliant center is a function of k_z, k_θ and θ. Thus to vary l_2 any of these three can be changed. To establish which of these parameters should be adjusted the reasons for having a variable l_2 are now examined in more detail.

If the robot picks up a larger gripper (or peg) an increase in l_2 is warranted. Since a larger gripper or peg is generally heavier an increase in k_z and k_θ is called for. In particular, the ability to *dynamically* vary l_2 makes part mating simple for a number of consecutive tasks.

From a design standpoint, it is much easier to dynamically vary k_z or k_θ than the angle θ. The length l_2 is

then a function of the ratio k_z/k_θ. In making a choice between increasing k_z or decreasing k_θ to increase the projection of the compliant center, the preference is to increase k_z since this increases the bending stiffness of the compliant wrist to match the larger moments imposed by a longer peg or gripper.

Based upon the above considerations, the authors propose an adjustable, instrumented compliant wrist which is simple, rugged and ideally suited to precision parts handling or assembly with a large industrial robot. Figures 5 and 6 show a simplified planar representation of the wrist. The lateral (radial) and axial springs are elastomeric spheres that resist compression but offer little resistance to lateral displacement. In order to improve the bending stiffness of the device, without sacrificing axial compliance in compression, Kevlar* cables are used as a tensile restraint. The Kevlar cables function essentially as pinned links in tension, but because they are also very flexible they offer no resistance to compressive or shear loading.

The first prototype of the sphere system consists of 45 mm diameter rubber spheres whose strength is increased by wrapping them externally with Kevlar thread. Typical force-deflection curves for these reinforced spheres are shown in Figure 7. As Figure 7 reveals, the stiffness of the spheres monotonically increases as force is applied. Thus for light loads the device is very sensitive; for heavier loads the sensitivity reduces and the stiffer system means that deflections are not excessive. The stiffness of the spheres can also be controlled by varying their internal pressure with a suitable fluid supply. For a given working load, increasing fluid pressure further increases stiffness.

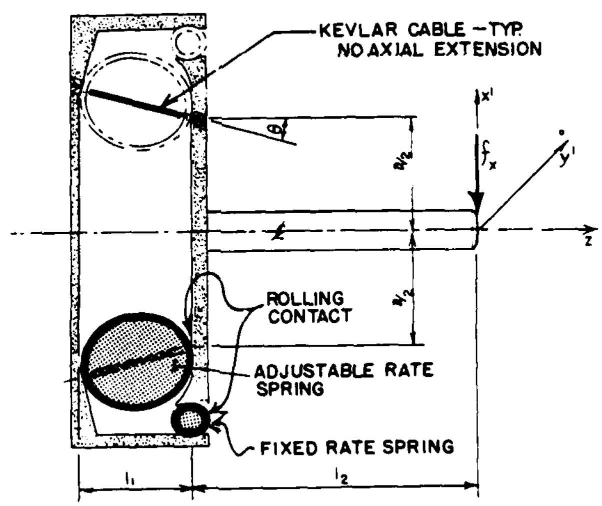

Figure 5: Planar view of new wrist

Figure 6 shows how the device reacts to a side load at the tip of a peg. The equations are very similar to those of the devices discussed earlier. The static force balance becomes:

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*Kevlar is a registered trademark of Dupont.

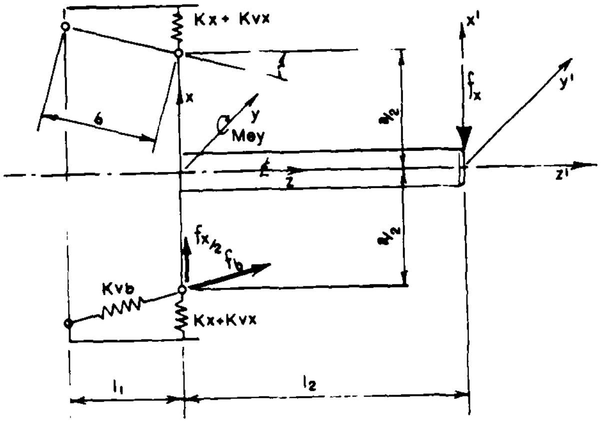

Figure 6: Spring representation of new wrist

$$M_{\theta y} = f_x l_2$$

$$f_b \cos\theta = f_x l_2 / a$$

$$f_L = f_x/2 - f_b \sin\theta$$

where f_b is the normal force exerted by the adjustable spheres and f_L is the net lateral force exerted by the radial spheres.

The force-deflection relations are:

$$\delta b = f_x l_2 / a k_{vb} \cos\theta$$

$$\delta x = f_x[1/2 - l_2 \tan\theta / a]/k_x$$

As the force f_x is applied to the tip of the peg the wrist deflects so that the cable in tension (at top) moves through an angle $\delta\theta$ while the adjustable sphere (at bottom) rolls along its inclined plane, $\delta y = \delta x \tan\theta$. At the same time the lower sphere compresses. If no rotational deflection is to occur, we have the following expression:

$$\delta b - 2\delta x \tan\theta = 0$$

Substituting for δb and δx gives l_2 in terms of k_{vb}:

$$l_2 = \frac{a k_{vb} \tan\theta}{k_x + 2k_{vb} \tan^2\theta}$$

In the three-dimensional case the actual force balance gives: $3/2\ f_b \cos\theta = f_x l_2/a$; since there are four adjustable spheres (Figure 1). Thus:

$$l_2 = \frac{3/2\, ak_{vb} \tan\theta}{k_x + k_{vb} \tan^2\theta}$$

For the design shown in Figure 1 an angle of $\theta \doteq 20$deg and $k_{vb} \approx 4k_x$ give good results.

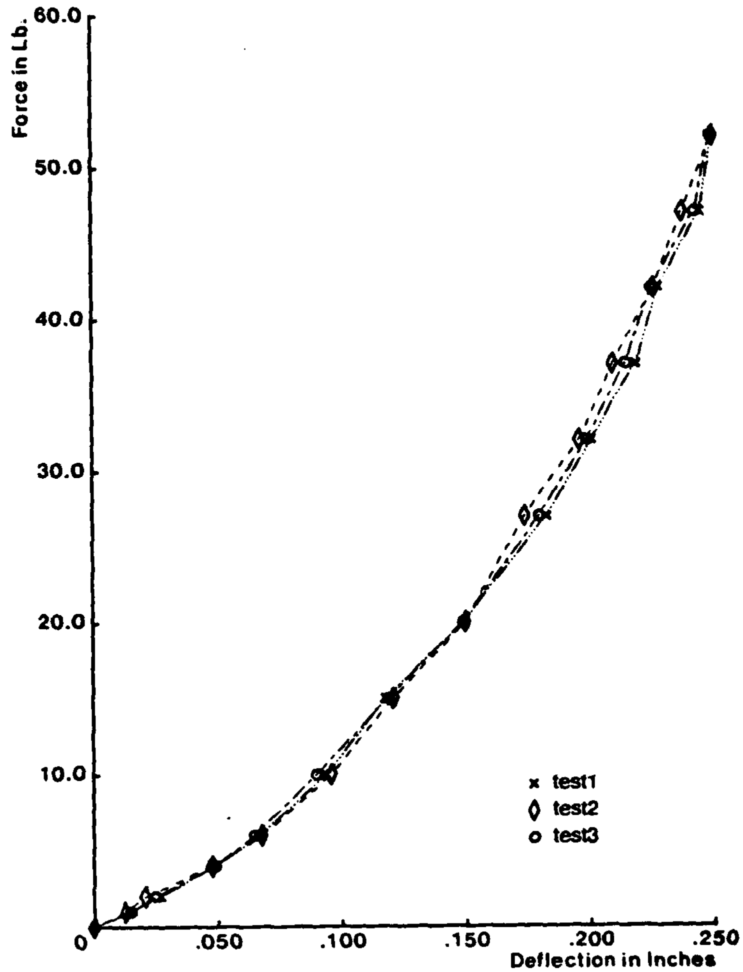

Figure 7: Force-deflection curves for reinforced spheres

2.5 System Control

The wrist design shown in Figure 1 is constructed and is undergoing preliminary testing on a Cincinnati Milacron T^3 Robot. This robot, like most other industrial robots, does not easily lend itself to real- time manipulator readjustment based on instrumented wrist information. The control system supplied with the robot is a modified position servo employing velocity feedback and some velocity feedforward to achieve faster response to commands. The dynamics of the robot show a 2 to 3 hertz bandwidth when subjected to disturbances and a 6 or 7 hertz bandwidth for input commands. [18] As expected, there is substantial cross coupling between the axes. In addition, the plant dynamics change considerably as a function of the robot's position. Without at least a partial real-time computation of the robot dynamics the responsiveness of the robot cannot be much improved. Although it is certainly desirable to improve the dynamic response of the

robot the difficulties associated with interfacing to the existing controller render this a long term goal. In the interim, a great deal can be accomplished using what is defined here as quasi-real-time modification of the robot path. A two phase project has been initiated to employ long term feedback in a way that is very close to the proposed stochastic control methods discussed by Whitney and Junkel.[16]

The first phase makes use of an available DDCMP interface option. Using this interface we modify sequences for the robot using programs written in the C language and running on a Vax 11/750. With this system, deflection data from the wrist are gathered as the robot performs a given task. Then while the robot is engaged in other tasks, or perhaps moving between work stations, the data are analyzed for systematic trends and the robot sequence is adjusted accordingly. Since the data are presented in "batch" form it should be possible to use a standard weighted least squares technique for analysis. [19]

One serious limitation to the above scheme is that errors cannot be corrected until a given task or sequence has been completed. Thus for example, though it may be possible to diagnose the rotational misalignment of a fixture after just a few steps into a sequence, it is impossible to correct for the misalignment until the robot is ready to enter the sequence a second time. For this reason, the first phase is viewed as a research operation for testing and verifying the algorithms that diagnose long term errors. The second phase of the control project eliminates this shortcoming. It requires a non-standard addition to the commercially available software that allows individual points to be updated while the robot is moving. In this scheme the wrist data become available sequentially, and therefore a recursive optimal estimator such as a Kalman Filter is used to extract significant trends from the information. Since the turn-around time for modifying a single point is fairly short it will be necessary to run the filtering, analysis, and coordinate transformation routines on a dedicated microprocessor. (Figure 9)

The two schemes mentioned above show how systematic errors may be corrected for; by contrast, non-systematic or random errors cannot be reduced in this way. Furthermore, the detection of, and correction for, systematic trends will inevitably be corrupted by sensor noise and by computational inaccuracies. Nonetheless, as the robot repeats a task over and over again there should be a steady improvement in its accuracy.

3 Concluding Remarks

This research is concerned with the development of general purpose wrist units for industrial manipulators carrying out assembly tasks that encompass a wide range of pay loads. The starting point for the new device shown in Figure 1 was a design by McCallion [4]. However, the straightforward construction of his wrist meant that the center of compliance was fixed at the compliant platform. The design presented here gives a variable length (l_2 in Figures 4 and 6) of the compliant center hence allowing the robot to work optimally with a range of gripper (or peg) lengths. Since the device is also instrumented, further position adjustment of the arm via the robot controller is possible in order to aid assembly of parts. The implementation of this system control via LVDT information remains an area for future work.

The human forearm is a manipulator of exemplary flexibility. When engaged in tasks requiring a range of

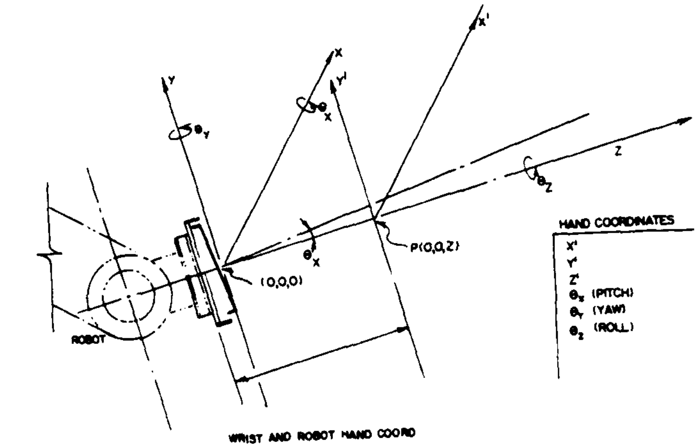

Figure 8: Coordinate system for robot control

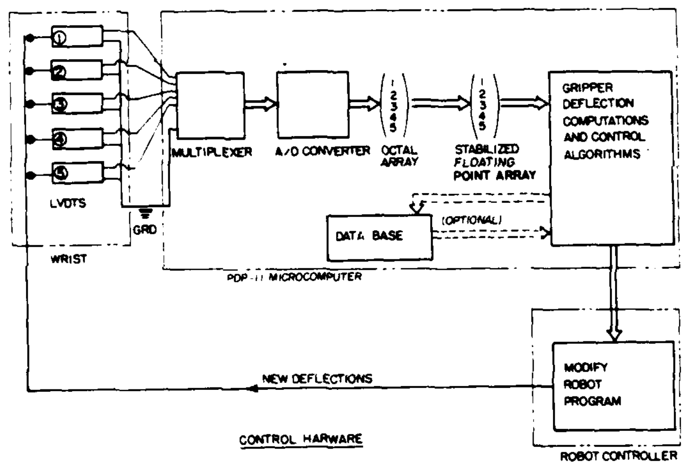

Figure 9: Analysis of LVDT signals

accuracy and force, it can call upon a range of muscles and use them in many configurations to vary strength or precision. The reinforced rubber spheres used for the springs in Figure 1 mimic very limited aspects of the human capability. The springs deliberately do not have linear force-deflection behavior. At low loads they are soft and responsive; as loads increase they become stiffer and incremently deflect less. Fluid has been used to stiffen the compliant spheres and the pressure may be varied automatically. This "mechanical programmability" allows compliant wrist devices to be more general purpose.

4 Acknowledgements

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